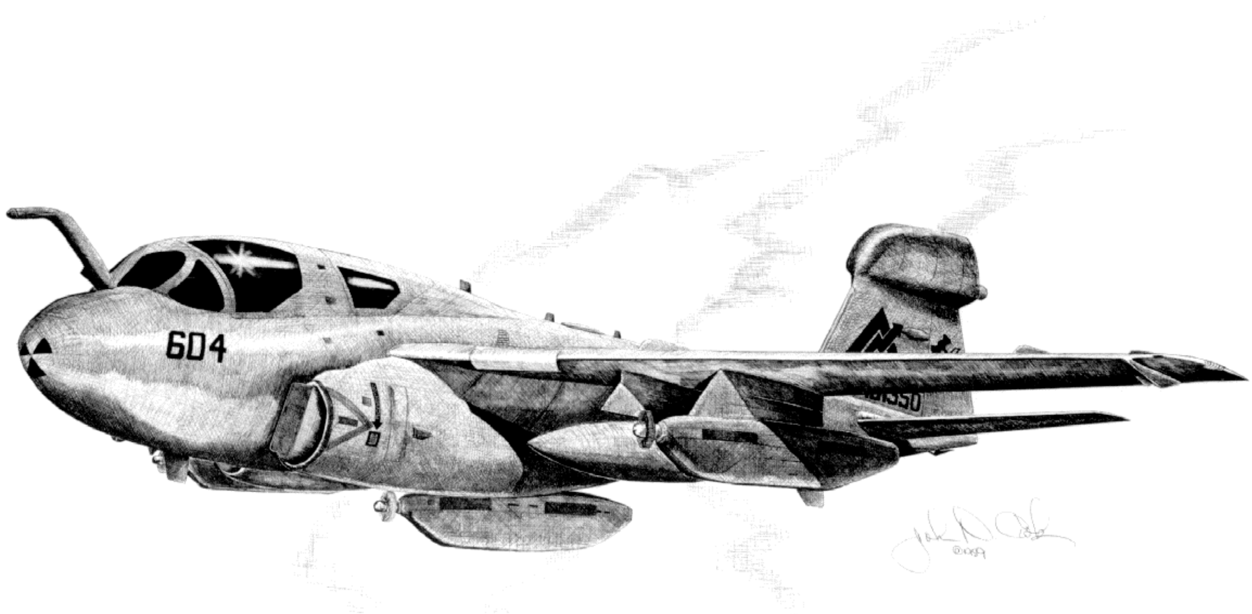
Application of RCM Analysis to Corrosion Failure Modes on the EA-6B Prowler Program



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ABSTRACT

The EA-6B is transitioning from the current Standard Depot Level Maintenance (SDLM) program to an Integrated Maintenance Concept (IMC) Program. The goal of the IMC Program is to increase aircraft availability, reduce overall maintenance cost, and improve aircraft material condition. As part of this transition, the EA-6B was subjected to a complete RCM analysis. This analysis addressed or will address all current preventive maintenance tasks as well as significant failure modes not currently addressed by preventive maintenance.

A significant portion of the RCM analysis performed on the EA-6B addressed corrosion failure modes. In fact, a significant portion of current maintenance down time and cost are incurred as a result of corrosion or attempting to prevent corrosion. Through the RCM analysis, the current maintenance philosophies and intervals dealing with corrosion were evaluated and updated. Additionally, specific preventive methods such as corrosion preventive compounds (CPC's) were applied to specific corrosion failure modes.

The purpose of this paper is to present the results of the RCM analysis on the EA-6B as it relates to addressing corrosion. The resulting maintenance program represents a fundamental shift from the previous methods of dealing with corrosion. This paper will present the changes to the EA-6B maintenance program and the results of those changes demonstrated though validated operating experience.

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REFERENCES

1. Society of Automotive Engineers Standard, SAE JA-1011, *Evaluation Criteria for Reliability-Centered Maintenance Processes*, August 1999

2. Naval Air Systems Command Instruction, NAVAIRINST 4790.20, *Reliability-Centered Maintenance Program*, May 3, 1999

3. Phillip L. Jones, F. Hadley Cocks, Duke University and Thomas Flournoy, FAA Technical Center, *Performance Evaluation of Corrosion Control Products*.

I. BACKGROUND

The EA-6B Prowler aircraft is a carrier based electronic warfare aircraft and is operated by USN and USMC squadrons. It is based in Cherry Point, NC and Whidbey Island, WA and operates on extended deployments from locations such as Japan, Saudi Arabia, and Italy in addition to its carrier based operations.

The existing preventive maintenance program, like that of most other USN and USMC aircraft, consisted of a series of flight hour and calendar based inspections at the squadron level. It was also inducted into a depot facility for Standard Depot Level Maintenance or "SDLM" on a conditional basis upon failing a material condition evaluation called "Aircraft Service Period Adjustment" or ASPA inspection. The main focus on corrosion at the squadron level was during a 28-day inspection. This inspection was a detailed zonal inspection with a significant panel removal and some other minor disassembly. Additionally, corrosion in the cockpit was addressed during a 224-day inspection in conjunction with ejection seat inspections that required their removal from the aircraft. Significant effort was spent identifying and repairing corrosion during SDLM. The aircraft was also stripped and painted during SDLM.

The Integrated Maintenance Concept (IMC) was developed to address budgetary and operational concerns with the current ASPA/SDLM program. For approximately the past 15 years under ASPA/SDLM program, material condition of aircraft was perceived as deteriorating. Additionally, because the depot induction criteria under ASPA/SDLM were condition based, depot maintenance budget requirements were unpredictable. As a result the CNO directed a change to IMC, which requires depot induction on a fixed calendar schedule. At the same time a recommitment to the principles of Reliability Centered Maintenance (RCM) was mandated under IMC.

RCM is an analytical process used to determine preventive maintenance requirements for a physical asset in its operating environment.[1] RCM is based on preserving the function of equipment by evaluating individual failure modes and the consequences of failure of that equipment. The goal of RCM is to provide the most cost effective maintenance program for a required level of safety and operational availability. Naval Aviation Systems Command policy requires that all preventive maintenance requirements be based on RCM analysis.[2]

The maintenance program for the EA-6B resulting from the RCM analysis included traditional squadron level maintenance inspections, depot field inspections performed by depot level personnel at the operational site, and induction of the aircraft into a depot facility. The depot field inspections occur every two years and the depot induction occurs every eight years. Disassembly during the depot induction is significantly more extensive than during the depot field inspections. The aircraft is stripped and painted during the depot induction.

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[1] Society of Automotive Engineers Standard SAE JA-1011, *Evaluation Criteria for Reliability-Centered Maintenance Processes* (August 1999).
[2] Naval Air Systems Command Instruction, NAVAIRINST 4790.20A, *Reliability-Centered Maintenance Program*, (May 3, 1999).

II. EA-6B CORROSION ANALYSIS

The existing preventive maintenance program, while satisfactory in terms of preventing catastrophic failure of aircraft structure due to corrosion, was far from optimum according to initial analysis. In reviewing the practices, philosophies, and results of the existing maintenance program, a number of observations immediately became evident:

- Because the existing 28-day inspection was almost entirely zonal in nature, a significant amount of effort was spent on areas that were not corrosion prone, or if they did corrode, were very slow growing if left alone.
- When corrosion was detected, especially in slow growing areas, the “cure” was often worse than the “disease”. Small areas of corrosion (or things that might be corrosion) were often mechanically removed along with larger portions of the surrounding protective coating. The removed coatings were usually replaced with inferior coatings.
- More frequent corrosion inspections were limited to areas easily accessed by the organizational level. Some of the more critical, more corrosion prone, and more expensive to repair areas were not looked at as often or at all.
- Repairs that required skills beyond the organizational level or required significant down time to accomplish were often deferred due to operational considerations or until repair resources became available. The result of this was that some of the more extensive, expensive, or severe corrosion discrepancies were left uncorrected for longer periods of time than less problematic discrepancies.
- The existing 28-day inspection required opening sealed panels at sea, increasing the likelihood of corrosion.
- The 28-day inspection introduced a significant amount of maintenance-induced damage. Some of this damage, such as the inevitable damage to panel seals or mechanical damage to painted surfaces (normal wear and tear from disassembly) also further increased the likelihood of corrosion.
- The 28-day inspection significantly impacted aircraft availability due to its frequency and depth.
- The focus of the existing maintenance was on detecting existing corrosion rather than preventing it. Preventive techniques such as the application of Corrosion Preventive Compounds (CPC) were used very little.

It should be pointed out that the above findings are general in nature and were not universal. It should also be noted that the above findings are in no way meant as a condemnation of the maintainers or quality of the maintenance actions being performed. In almost all cases, the observations above were the result of the existing maintenance requirements being performed as directed by existing technical documentation and training.

After the initial review of the existing maintenance program it became obvious that improvements could be made. We concluded that improvements would be best accomplished by addressing two issues:

1) Evaluate the interval and scope of the primary corrosion inspection
2) Focus more on prevention rather than correction.

As stated previously, RCM analysis is the primary means to determine appropriate inspection requirements and intervals. Also as stated previously, RCM analysis is performed by analyzing specific failure modes. In order to effectively evaluate the current maintenance tasks, we adopted the following analysis approach:

1) We identified and analyzed general corrosion failure modes for each area of the aircraft. These areas corresponded to the zones inspected during the 28-day inspection
2) We also identified and analyzed failure modes for each known specific corrosion prone area. These corrosion prone areas were identified by interviews with fleet maintainers and depot artisans, review of Navy 3M data and depot repair records, and review of formal failure reports.

General corrosion failure modes included the type of discrepancies usually found and repaired during the 28-day inspection. The analysis of these discrepancies showed that all but a few did not affect safety or structural integrity in any way, were not fast growing, and would not be significantly more costly to repair even if left uncorrected for periods of time much longer than 28 days. This conclusion was reached based on the types of corrosion found, the types of items found corroded, and known and observed corrosion growth rates. The analysis began to show that the inspection interval for general corrosion failure modes could be significantly increased. The next question was: “what is the proper interval?”

Inspection intervals determined through RCM analysis are based on the “potential” to “functional” failure or (PF) interval of the failure mode. In summary, this is the interval between the point when symptoms of an impending failure can be detected to the point at which some function is lost. Corrosion PF intervals are hard to define because rarely is the function of an item lost due to corrosion, except over very long periods of time. Exceptions to this may be in highly loaded primary structure where corrosion may lead to structural failure, but even that is usually in terms of years not weeks. Typically, for analysis purposes, the functional failure of a corrosion failure mode would be defined as the point at which it requires excessive downtime or expense to repair. This is a conservative approach since it is usually long before any safety implications exist.

Recognizing that we were only considering general corrosion failure modes at this point in the analysis, and that we could analyze separately any specific failure modes that were deemed too severe to inspect at whatever interval we chose, we began to consider general corrosion inspection intervals. We began this process by evaluating other Navy aircraft maintenance programs and their performance, as well as other aircraft, and other equipment subject to corrosion. Major corrosion inspection intervals for other US Navy aircraft ranged from 56 to 308 days. Intervals for other aircraft and equipment ranged from months to years. Inspection interval length on aircraft did not appear to have any identifiable relation to aircraft condition.

One additional piece of data supporting the extension of the 28-day inspection was a study on the A-6E aircraft that allowed one A-6E squadron to prototype a 6-month corrosion inspection interval. That study showed no significant change in aircraft material condition from the extension of the interval to six months.

Based on all the information compiled, we decided that a general corrosion inspection could be extended to anywhere from six months to well over a year and would still provide adequate protection for the PF interval of the failure modes in question. We also concluded that an extended interval that would minimize aircraft disassembly aboard ship would actually reduce the occurrence of corrosion. Furthermore, the longer the inspection interval, the less maintenance induced damage, and therefore less corrosion. We chose one year (364 days) for the inspection interval. This interval was the shortest interval that would effectively eliminate the need to perform the inspection while deployed based on the typical operational schedule of the EA-6B Prowler.

With the general corrosion inspection interval resolved we began to focus on specific corrosion problem areas. Although dozens of specific corrosion failure modes were analyzed, there were five that resulted in significant action beyond inspecting during the new 364-day inspection.

1. <u>Lower longeron</u>. One area of the lower longeron was found to have significant corrosion occurrence and severity. This area was exposed to the environment in the nose wheel well. Additionally, the physical configuration of this longeron compounded the corrosion problem. The longeron makes a channel that allows water to pool in it. While portions of the channel are visually accessible, other portions are covered by other structure precluding inspection. When corrosion occurs in these hidden areas, extensive disassembly is required to effect repairs. It was obvious that even the current 28-day inspection was ineffective in managing this failure mode. The analysis concluded that this area was an ideal situation for application of a CPC. The resolution to this failure mode was application of CPC with a wand applicator that allowed application to hidden areas. Due to the special equipment required, the type of CPC being applied, and the required reapplication interval of the CPC; it was decided to apply the CPC in this area during the two-year depot field event. See discussion of CPCs below.

2. <u>Upper longeron.</u> The upper longeron inside the cockpit is a box beam made up of two c-channels. While parked with the canopy open, the EA-6B often gets a significant amount of rain water in the cockpit. Aboard ship the EA-6B can get rain and/or saltwater spray into the cockpit. Finally, there is often significant leakage of water around the canopy seals. Corrosion has been found in several aircraft inside the longeron structure. This corrosion was usually found during depot maintenance when extensive disassembly was performed. Repair of even minor corrosion would require extensive disassembly. Like the lower longeron, the analysis concluded that this area was an ideal situation for application of a CPC. The CPC is applied with a wand applicator that allows application to the inaccessible areas. Inspection and repair, if necessary, is performed during the depot induction.

3. Cockpit Floor. The cockpit floor consists of floorboards and a sub-floor. Flight control linkages, wiring harnesses, and hydraulic tubes run between the floorboards and sub-floor structure. As discussed earlier, the cockpit is subject to significant water intrusion. In fact, there is often standing water both on the cockpit floor and sub-floor. Repairs of the sub-floor are problematic due the need to remove or work around flight control linkage, wires, and tubes. Removal of any of these items requires systems operational tests and/or rigging checks. Additionally, access to most of the sub-floor requires removal of the ejection seats. Inspection for corrosion in this area was previously accomplished during the 224-day inspection, which required ejection seat removal. Finally, we determined that the existing coating on the sub-floor consisted of a primer and an interior paint. The solution identified for this failure mode was a CPC application during the field depot event, an improved paint system for the sub-floor applied during the depot induction, and inspection and corrosion treatment during the 364-day inspection.

4. Tailfin Pod. The tailfin pod, also known as the "football", contains various electronic components. The structure of the football consists of aluminum skin, ribs, and brackets. The structure is enclosed in a fairly confined space and has many faying surfaces between the various skins, ribs, and brackets. The internal area is intended to be sealed but often showed evidence of water intrusion. Aboard ship, aircraft are often parked with tails hanging over the side of the ship exposing this area to heavy saltwater spray. Crevice corrosion was frequently found between various fayed surfaces. This was previously inspected for during the 28-day inspection. However, due to the difficulty in inspecting the area and detecting corrosion if present, repairs were usually only performed at SDLM. The solution to this failure mode was inspection and application of a penetrating CPC during the 364-day inspection.

5. Honeycomb surfaces. Aluminum honeycomb core structure is used throughout the EA-6B aircraft. Typical applications include flight control surfaces and skin panels. Significant expense was incurred at SDLM repairing corroded honeycomb core. Many of the corroded panels had significant quantities of water entrapped in the core. Tap tests of honeycomb structure were performed at SDLM and sporadically in the field at other maintenance intervals. Although there was no specific requirement to perform tap tests, they were typically done as standard maintenance practice during zonal inspections. Because most defects were found at SDLM, when corrosion did occur it was usually very extensive. Scrap rates of flight control surfaces were very high. RCM analysis determined that a two-year tap test would detect corrosion and delamination defects at an early stage thereby saving components and reducing cost. Therefore, a tap test for all honeycomb structure was added to the field depot IMC event.

As discussed above, CPCs were one of the primary methods used to address specific corrosion failure modes. A significant amount of effort was spent evaluating which product to use for each of the specific areas analyzed. A study of often-used CPCs in the aviation industry concluded that most of the products in their study were effective in reducing corrosion. The study compared performance of these products in a salt spray chamber. The study showed that performance was closely related to viscosity of the product in this particular test environment. It also recognized that with reapplication of product at appropriate intervals, performance would probably be very similar[3].

Based on the specific corrosion failure modes we analyzed, we selected two different CPCs. As discussed previously, the tailfin pod area consisted of faying surfaces in tight quarters. We selected a water-displacing fluid film product for this application. The other locations were all either in external areas subject to erosion of the coating or areas subject to standing water. For these areas a water-displacing hard film product was selected. Another consideration in selecting products was maintenance personnel preference. We received negative feedback from maintainers who were familiar with non-drying hard film products due to the accumulation of dirt in the CPC. Because we would be using these in areas accessed for other maintenance, such as the cockpit floor area, we selected a drying hard film product. Other factors impacting our product selection included availability in the Federal supply system, hazardous material considerations, and the experience of other US Navy aircraft programs.

One additional improvement that was incorporated was the use of Skyflex™ sealant in place of traditional form-in-place seals. With its better sealing characteristics and reparability, Skyflex™, in addition to the reduced opening of panels, would further decrease exposure of internal compartments to corrosive environments.

Lastly, it should be noted that RCM analysis is a continuous process. It includes monitoring of the results of its recommendations. Should any of the solutions determined through the initial analysis be deemed ineffective or suboptimal, they will be adjusted as better information becomes available. Likewise any new corrosion prone areas or areas that were missed in the original analysis will be identified through monitoring and analyzed as necessary.

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[3] Phillip L. Jones, F. Hadley Cocks, Duke University and Thomas Flournoy, FAA Technical Center, *Performance Evaluation of Corrosion Control Products*.

III. RESULTS

The method used for evaluating results from the change in maintenance philosophy involved significant data collection and analysis. The idea was to compare the new maintenance program to previous program via actual operational data and analytical estimates. Analytical estimates of maintenance program performance had been developed during the RCM analysis, and the actual data would be pulled from various sources such as the Navy 3M system, survey reports, and fleet feedback.

Four aircraft from Electronic Warfare Squadron (VAQ) 140 were the first to transition to the RCM based IMC concept. Transition was accomplished by performing an initial depot field event. The first four aircraft were tracked closely during their first year in service following the initial depot field event. Inspection results from the first 364-day inspection following the depot field event were gathered for analysis. Evaluation of the maintenance program is ongoing. These data will continue to be evaluated for the IMC events as well as the 364-day special inspections.

Analytical Comparison.

As the initial RCM process was completed, each task and interval had an associated impact in terms of projected maintenance man-hours (MMH) and out of service (OOS) time. Changes to the 28, 56, 224, and 364-day maintenance packages were evaluated in terms of MMH required for each inspection and the subsequent projected OOS time. These maintenance packages were the ones significantly changed as a result of the RCM analysis. Therefore, overall impact of the changes can be estimated by summing the changes to each of these inspection packages. Table 1 shows the analytical comparison of maintenance program changes over a 2-year period, for a 4 aircraft squadron once it has fully transitioned to the IMC concept.

	INTERVAL (DAYS)	INTERVAL WORKLOAD (MMH)	2 YR CYCLE (MMH)	INTERVAL OOS TIME (DAYS)	2 YR CYCLE (DAYS)
Pre IMC	28	93	4836	3	156
	56	126	6552	5	260
	224	194	2328	5	60
		SUM	13716	SUM	476
IMC	28	14	728	0.5	26
	56	11	572	0.5	26
	364	200	1600	5	40
		SUM	2900	SUM	92
		DECREASE	78.86%	DECREASE	80.67%

Table 1: Squadron 2 Year Cycle MMH and OOS

The decrease in MMH and OOS time due to the RCM generated changes is significant. However, it should be noted that this is an analytical view that does not include any extenuating factors such as other delays due to other squadron workload, delays awaiting parts, or corrective actions required. Although no corrective action times were included, we assume these would only improve the numbers since RCM generated tasks should result in improved material condition. The actual operational and maintenance data and OOS times were used to validate this assumption. Although a significant portion of these changes are related to corrosion, it should also be noted that the analysis above pertained to all maintenance changes related to IMC, not just those associated with corrosion. The actual data comparison below will focus more closely on corrosion.

Actual Data Comparisons.

Operational and maintenance data from the Navy 3M system were used to evaluate the actual impact of all of the RCM based maintenance changes. Additionally, this data was used to evaluate the specific impact of changes to corrosion inspections. Five categories of actual data are used to accomplish this:

1) OOS Time (measured)
2) Corrosion prevention MMH expended
3) Corrosion correction MMH expended
4) Formal fleet reports on prototype aircraft
5) Informal fleet feedback

1. OOS Time (measured). To compare the analytical estimates of OOS time with actual fleet experience, Navy 3M elapsed maintenance times (EMT) were used. EMT for scheduled inspections at the affected intervals were compiled for a 12 month period prior to and after the IMC transition events for the first 3 of the 4 VAQ 140 prototype aircraft, and for an 8 month window for the aircraft that has not yet had a second 364 day inspection. Table 2 shows the results.

	BEFORE	AFTER	DECREASE
163884	118	25	78.81%
163403	88	34.5	60.80%
163402**	56	22	60.71%
163522	96	29	69.79%
4 aircraft average			67.53%

* Total EMT (in days) for 28, 56, 224 or 364-day inspections 12 months before and after IMC conversion. The month of the conversion was excluded.
** 8 months vice 12

Table 2: EMT comparison for VAQ 140

The data show a marked decrease in out of service time due to scheduled maintenance. While OOS time is only one measure of the benefit due to RCM, it shows that the projected analytical results were realized in service.

2. Corrosion Prevention MMH Expended. Corrosion prevention efforts include washing, CPC application, and paint touch-up. Corrosion prevention MMH are also tracked in the Navy 3M system. Initially one might expect that this metric would decrease with the increased corrosion inspection interval. However, this was not actually the case, for a number of reasons. The prototype squadron deployed shortly after conversion to the 364-day cycle. An increase in the number of wash cycles, as required while aboard ship, and increased CPC application to the landing gear are two examples of items contributing to increased documented corrosion prevention. For any squadron transitioning to the IMC program, the scheduled maintenance requirements would be lessened, but the same number of personnel and therefore, MMH would still be available for work on the same aircraft. In addition, with the implementation of IMC there has been an increased emphasis on corrosion prevention. The fact that MMH are being charged now to corrosion prevention instead of corrosion correction or scheduled maintenance is both expected and positive. Table 3 shows the change in corrosion prevention MMH before and after IMC conversion.

	MMH BEFORE	MMH AFTER	INCREASE
163884	823	2,051	
163403	2,488	2,466	
163402	1,625	3,850	
163522	2,643	2,109	
4 aircraft average			38.22%

Table 3: Corrosion Prevention MMH Comparisons

It is clear from the increase in corrosion prevention MMH that there is a change once the aircraft have converted to the IMC program. The increase is not consistent over all aircraft, and it should be noted that BUNO 163884 was not with VAQ 140 prior to the conversion to 364-day cycle. A more consistent trend is expected from a squadron that has had the same aircraft before and after IMC transition.

3. Corrosion Correction MMH Expended. Navy 3M data were once again used here to compare transition to IMC. Corrosion correction is tracked in terms of MMH charged, and this includes discrepancies found outside of the 364-day events. This gives a more complete material condition picture. Table 4 shows a direct MMH comparison by BUNO for the equivalent time period before and after IMC transition.

	MMH BEFORE	MMH AFTER	DECREASE
163884	8,409	571	93.21%
163403	1,612	470	70.84%
163402	2,628	914	65.22%
163522	2,054	1,194	41.87%
4 aircraft average			67.79%
3 aircraft average (w/o 163884)			59.31%

Table 4: Corrosion Correction MMH Comparisons

The chart shows a marked decrease in corrosion discrepancies for the first 4 IMC prototype aircraft. Aircraft 163884 was not with VAQ 140 for the entire 12-month period prior to IMC transition, so its numbers cannot be expected to be consistent with the other 3. For the other 3 aircraft, there is a 59% drop in MMH involved with correction of corrosion discrepancies.

4. Formal Fleet Reports on Prototype Aircraft. At the present time 3 of 4 aircraft have reported the findings from their first 364-day event following IMC implementation. VAQ 140 was asked to provide a detailed description of discrepancies, findings, and a condition assessment to the EA-6B FST upon completion of the first 364-day event under the IMC philosophy. The findings are positive in that there is no significant increase in time to perform inspections, correct defects, or return the aircraft to service. Specific areas of concern included the ejection seats and the cockpit floor. Seat surveys were developed by the FST and submitted by the squadron. Results from the surveys are positive. The indications overall are that the material condition of the aircraft is at least as good as it was under the pre-IMC philosophy.

5. Informal Fleet Feedback. Feedback has been encouraged from IMC coordinators who track events at NAS Whidbey Island and MCAS Cherry Point, and squadron personnel whose aircraft have transition to IMC. They have given favorable feedback to the IMC process and the supporting RCM analysis. They cite improved time out of service, general aircraft condition, reduced maintenance effort, ease of inspection, and discrepancies found. Maintainers indicate the use of Skyflex™ sealant on a number of regularly opened panels has provided an additional benefit to them. They state Skyflex™ has shown durability in use so far, in addition to saving time during application. There have been suggestions to refine inspection procedures and requirements, but overall response has been positive.

IV. CONCLUSIONS

The results of the EA-6B maintenance requirement changes to date have been positive across the board. While the sample size is still small, we have no reason to believe the current data will not be representative of the results from the rest of the fleet. Extension of the general corrosion inspection interval has not negatively impacted material condition of aircraft and has decreased required maintenance effort while increasing aircraft availability.

Based on the results of the EA-6B, we believe that other programs may benefit significantly by reviewing their approach to corrosion control. Aircraft with general corrosion inspection intervals of less than one year may benefit from extension of that interval. Of course, optimum intervals may vary significantly by program and depend on a myriad of factors.

Specific corrosion prone areas should be analyzed via RCM analysis. RCM analysis provides the vehicle to compare all of the possible solutions to a specific corrosion failure mode. Solutions such as redesign, CPC application, inspection, and many others can all be evaluated through RCM. Analyzing each specific corrosion prone area separately allows the optimum solution to be implemented for each. There are no magic bullets for all cases.

Finally, an effective RCM Program depends on continuous monitoring and update as necessary. Processes must be put in place to monitor the maintenance program and update analysis as new failures are identified, initial assumptions are refined, and external factors change.

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